Results Outbrief from the 2014 CombustionLab Workshop

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November 13, 2015

Goals

- Provide the community with an update of the outcome of the 2014 CombustionLab workshop and subsequent prioritization

Milestones

- FluidsLab and CombustionLab NSPIRES RFI released: May 13, 2014; closed September 24, 2014
- Liquid Crystals NSPIRES RFI released: May 23, 2014; closed June 20, 2014
- Liquid Crystals Workshop conducted at the 25th International Liquid Crystal Conference in Dublin, Ireland, June 27, 2014
- Two-Phase Flow Workshop conducted at the 9th International Conference on Two-Phase Systems for Ground and Space Applications, Baltimore, MD, September 22, 2014
- FluidsLab and CombustionLab Workshops conducted at the 30th Annual Meeting of the American Society for Gravitational and Space Research, Pasadena, CA, October 24 - 25, 2014
- Recommendations presented to NASA HQ SLPS: March 10, 2015
- Final Report released: Spring 2015
- Strategic Plan completed: Summer 2015

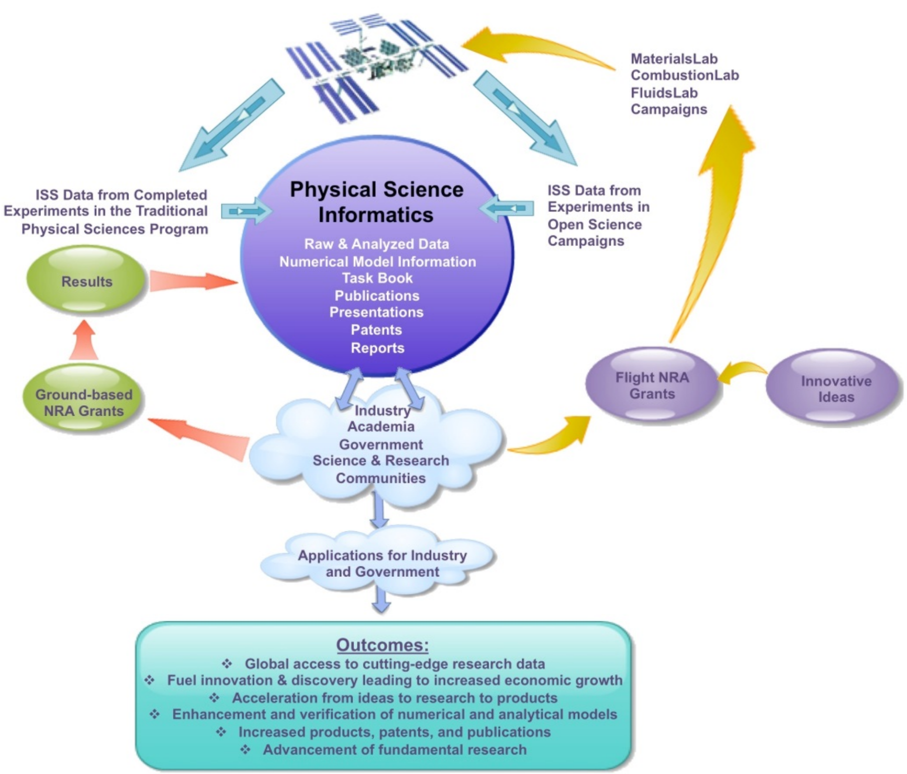
Participant Highlights

- CombustionLab Workshop at the 30th ASGSR
  - ~80 people from the academic, industrial, government and international communities, etc., etc.
- FluidsLab Workshop at the 30th ASGSR
  - ~100 participants from the academic, industrial, government and international communities
- Two-Phase Flow Workshop at the 9th ITTW2014
  - ~50 participants from the academic, industrial, government and international communities
- Liquid Crystals Workshop at the LC2014 Conference
  - ~100+ participants from the academic, industrial, government and international communities

The World's Forum for Aerospace Leadership

CombustionLab and FluidsLab – Vision From Microgravity Science to Open Science Informatics

- Fully utilize ISS as national laboratory to conduct microgravity combustion and fluids research and disseminate data into open science informatics, to accelerate development of combustion- and fluids-based technologies for NASA and the nation, and enhance STEM education.



- **Access to global science/engineering community**
- **Simultaneous rapid multiplicative investigations**
- **Break-through scientific advance of real value**
- **World-wide STEM education opportunity**
- **Low-cost and high-throughput research**
- **Use of existing facilities as much as possible**
- **Minimum Astronaut intervention and time**
- **Visible, applicable, and high return on investment**
- **Industry-driven engineering fulfillment**

Purpose: scientists identify/design most promising combustion and fluids experiments, in sync with engineers

Goal: Provide needed combustion and fluids science data and knowledge to enable advanced technologies and application on Earth and for space exploration

Open Science and Informatics: Inspire new areas of research, educate students, enhance discovery and multiply innovation

NASA CombustionLab Workshop – Six Themes and Session Leads

- **Spacecraft Fire Safety**

  Chairs: Paul Ronney (University of Southern California), Gregory Linteris (NIST); NASA Facilitators: Sandra Olson, Paul Ferkul, Gary Ruff

- **Droplets, Sprays and Aerosols**

  Chairs: Arvind Atreya (University of Michigan), Meredith Colket (UTRC); NASA Facilitators: Daniel Dietrich, Vedha Nayagam

- **Premixed Flames**

  Chairs: Elaine Oran (University of Maryland), Narendra Joshi (GE); NASA Facilitators: Suleyman Gokoglu, Fumiaki Takahashi, Uday Hegde

- **Non-premixed Flames**

  Chairs: Kal Seshadri (University of California San Diego), Chiping Li (AFOSR); NASA Facilitators: Dennis Stocker, Fumiaki Takahashi, Uday Hegde

- **Heterogeneous Reaction Processes**

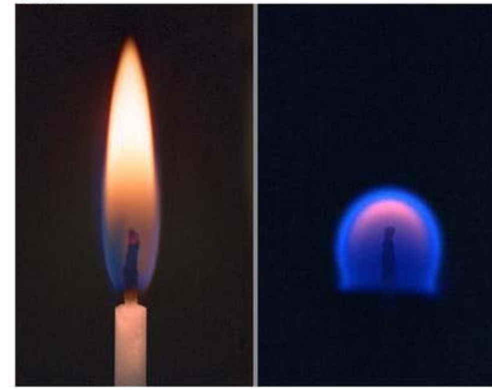
  Chairs: Hai Wang (Stanford University), Christopher Shaddix (Sandia National Laboratories); NASA Facilitators: Suleyman Gokoglu, Vedha Nayagam

- **High Pressure and Supercritical Reacting Systems**

  Chairs: William Jacoby (University of Missouri), John Deur (Cummins, Inc.); NASA Facilitators: Michael Hicks, Uday Hegde

Combustion Research
Microgravity Justification

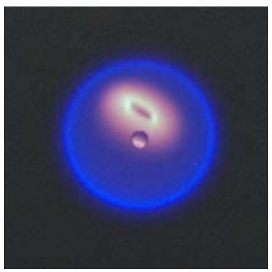
"The effects of buoyancy are so ubiquitous that we generally do not appreciate the enormous negative impact that it has had on the rational development of combustion science" C. K. Law and G. M. Faeth, National Academy of Engineering.



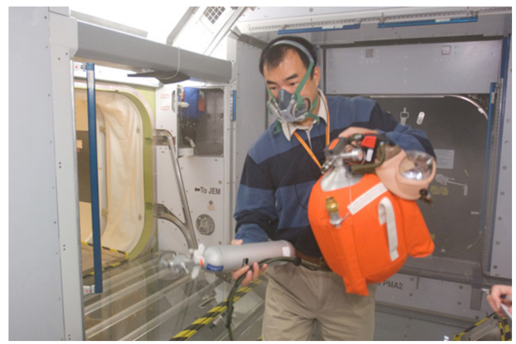
(a) (b)

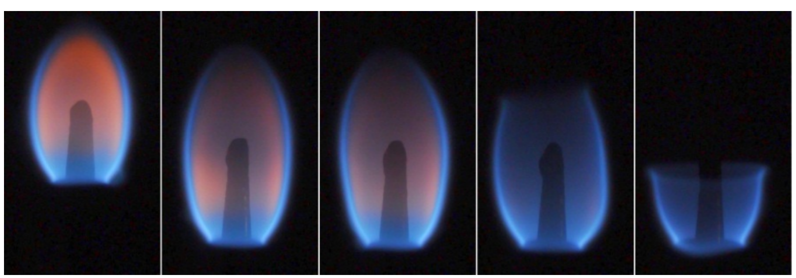
Candle flame (a) in normal gravity and (b) microgravity..

All Flame Processes are impacted by gravity



1-Dimensional Spherical geometry attainable in low-g





Flammability is enhanced at the low ventilation or buoyant flows only accessible in reduced gravity.

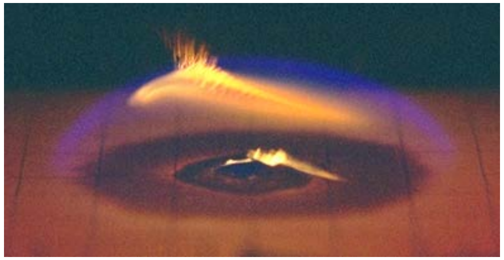
All processes from ignition, detection to extinguishment are different in low-gravity

Recommendations

Spacecraft Fire Safety

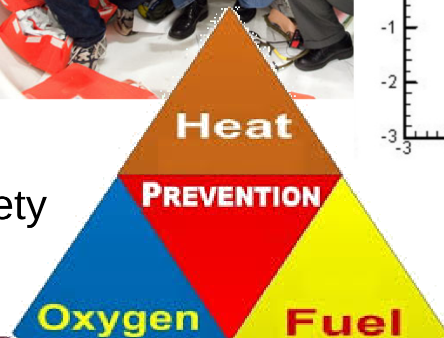
1) Material Flammability in Exploration Atmospheres
2) Fundamental Processes in Material Flammability
3) Full Scale Fire Behavior In Low-gravity

Chair: Paul Ronney / University of Southern California
Co-chair: Gregory Linteris / NIST
Facilitated by: Sandra Olson, Paul Ferkul, & Gary A. Ruff

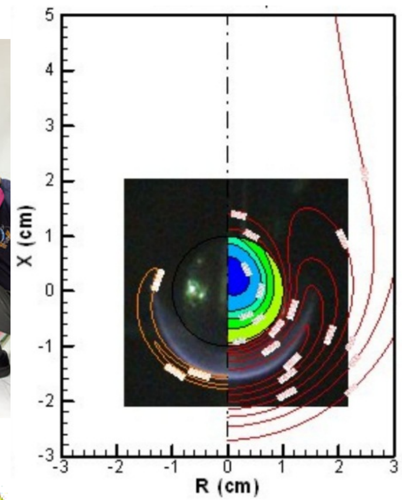


Spacecraft Fire Safety
Applications

Detection and suppression



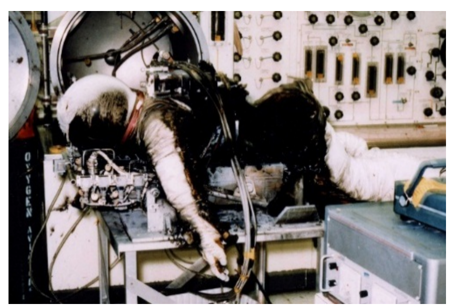
Crew Safety



Modeling

Materials Flammability Screening

Vehicle Integrity



High Pressure Oxygen Systems

Spacecraft Fire Safety
Material Flammability in Exploration Atmospheres
Rank: High Priority #1

Objective

Determine the flammability limits of materials in microgravity at atmospheres planned for exploration vehicles to validate 1-g test methods.

NASA Relevance

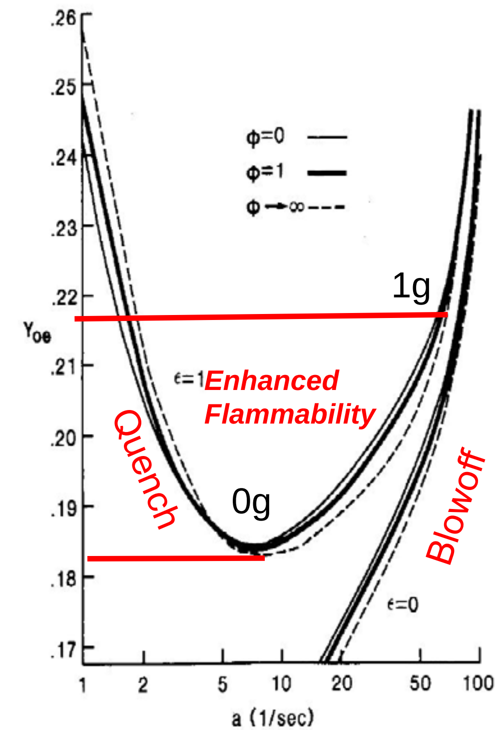
An understanding of the relationship between the 1g flammability tests and actual microgravity fire behavior of the materials will provide a scientific basis for the use of the tests, and help to better define the margin of safety in existing approaches.

Impact/Applications - Exploration

- Fire is one of the major risks for loss of vehicle or crew.
- Improved understanding of materials flammability in space will reduce the risk of fire by providing operational changes and mitigation strategies to stop a fire from starting in the first place.
- Requested by HEOMD stakeholder.

Facilities

Exploration atmospheres can be studied in CIR with the SoFIE insert.



Flammability boundary in forced, buoyant and mixed convective flows. Foutch and T'ien, 1987

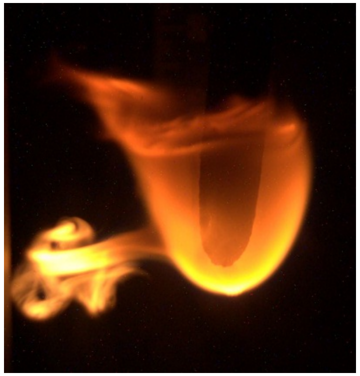
Spacecraft Fire Safety
Fundamental Processes in Material Flammability
Rank: High Priority #2

Objective
To quantify the effects of material properties, geometry, proximity to other materials, and flow orientation on the burning behavior in microgravity.

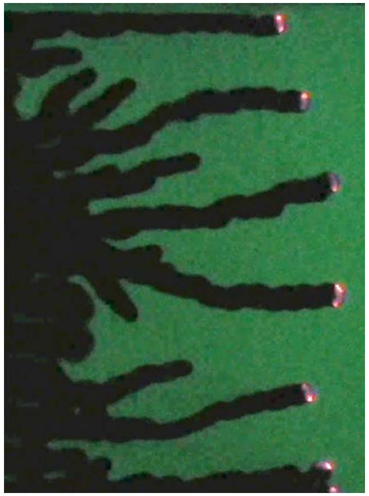
NASA Relevance
Decomposition behavior, vapor jetting, molten dripping or flow, expansion, etc. in microgravity have a large effect on the oxidizer flow-field and mass transport at the surface. These complex behaviors of burning materials can have a large impact on the severity of the fire risk in a spacecraft. Test samples that correspond to the NASA standard test can only be conducted in a new facility

Impact/Applications – Exploration and Earth-based
- The complex burning behavior of real materials can be best elucidated using simplified geometries in a well-controlled long-duration microgravity environment.
- The complex burning phenomena of real materials in microgravity is one of the largest deficiencies in existing models of spacecraft fire scenarios.

Facilities
Different geometries, materials, and flow directions can most effectively be studied in a new Microgravity Wind Tunnel (MWT) in the Microgravity Science Glovebox.



High velocity fuel vapor jets catch fire in the flame zone.



Fingering flame spread

Spacecraft Fire Safety
Large Scale Fire Behavior in Low-Gravity
Rank: High Priority #3

Objective

To quantify the initiation and growth of a large-scale fire in a space vehicle and demonstrate the performance of spacecraft fire safety technologies developed for NASA's exploration missions.

NASA Relevance

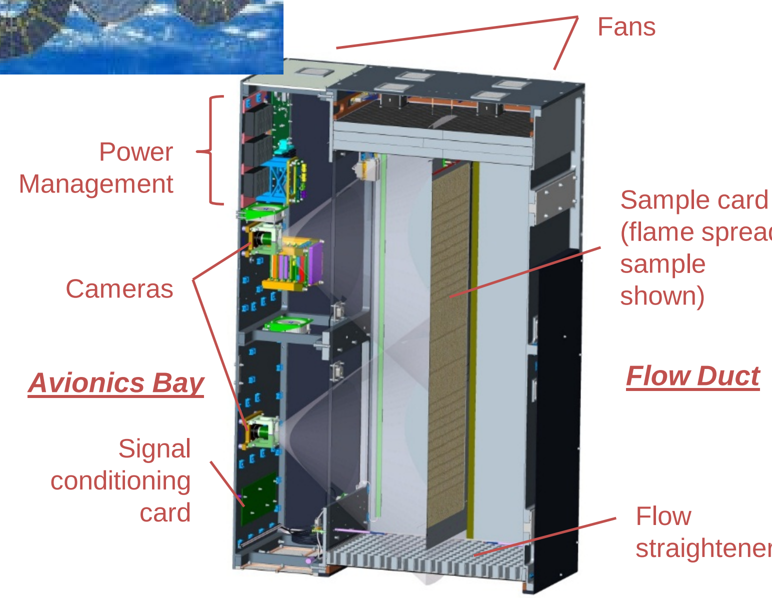
The real hazard for fire safety in spacecraft is a large, uncontained fire in a small crewed vehicle. Understanding how to best protect the crew and provide them with effective fire response technologies requires that these fires be studied on a realistic scale, similar to testing performed on terrestrial transportation systems.

Impact/Applications - Exploration

- Data from planned tests will quantify large-scale flame spread and be used to validate models of spacecraft fire scenarios
- Future tests can validate design assumptions for spacecraft fire response systems and demonstrate fire detection, suppression, and post-fire cleanup technologies for exploration systems

Facilities

Experiment will be conducted on an uncrewed ISS re-supply vehicle after leaving ISS.



Dimensions of the Saffire hardware (above) are approximately 53- by 90- by 133-cm. Three Saffire flights will be conducted on Orbital's Cygnus vehicle (inset) starting in FY16. Additional flights are planned to demonstrated spacecraft fire safety technologies.

Recommendations

Droplets, Sprays and Aerosols

1) High Pressure (Super and subcritical) Droplet Combustion
2) Cool Flame Combustion of Liquid Fuels
3) Biofuel combustion and Liquid-Phase Circulation and Diffusion Measurements

Chair: Arvind Atreya / University of Michigan

Co-chair: Meredith Colket / UTRC

Facilitated by: Daniel Dietrich & Vedha Nayagam

Droplets, Sprays and Aerosols
Applications

HCCI Engine
(Homogeneous Charge Compression Ignition)

In engines: **timing is everything**

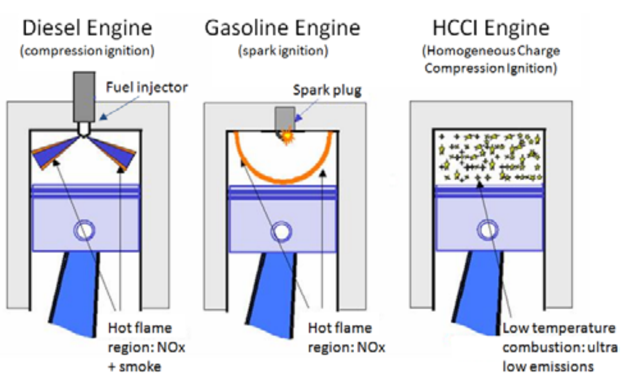
Low-gravity gives the opportunity to evaluate the chemical kinetics and transport needed to control the interactions between these processes and the bulk flow in engines

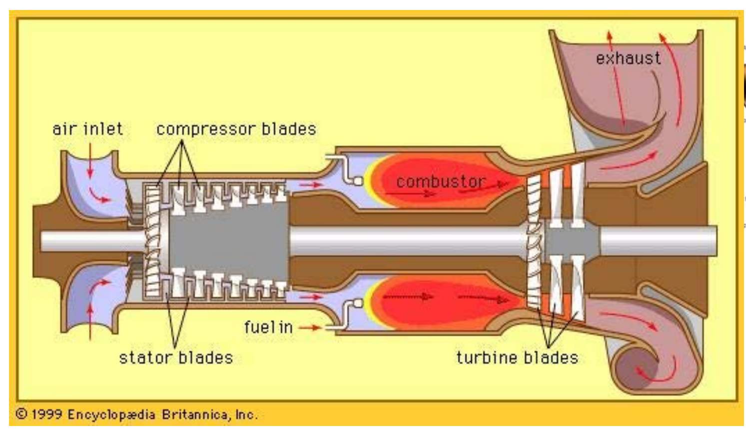
e.g.:

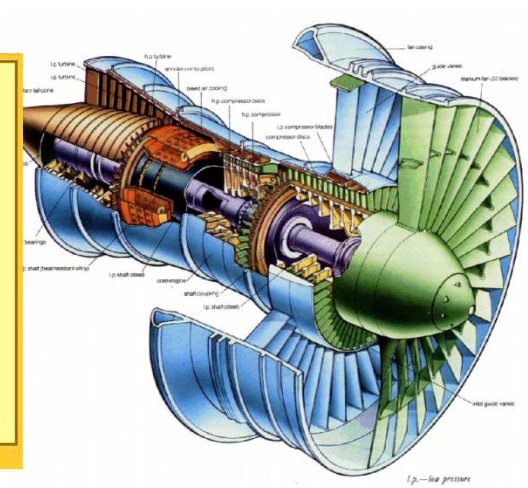
Knock versus non-ignition (diesel)

Delayed ignition (followed by explosion)

Flame out







Droplets, Sprays and Aerosols

High Pressure (Super and subcritical) Droplet Combustion

Rank: High Priority #1

Objective

Obtain benchmark data on the vaporization and combustion of droplets in sub- to super-critical conditions. Improve the fundamental understanding of the sub- to super-critical transition for single droplets and develop sub-models for complex CFD design codes.

Relevance

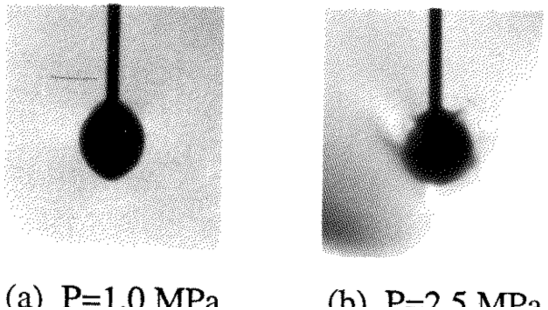
Virtually all practical combustors operate at high pressures due to higher thermodynamic efficiencies. High pressure combustion in the sub- to super-critical transition region poorly understood. Difficult to study under normal gravity due to increased buoyancy effects and reduced surface tension. Fundamental data needed to improve modeling of real combustors.

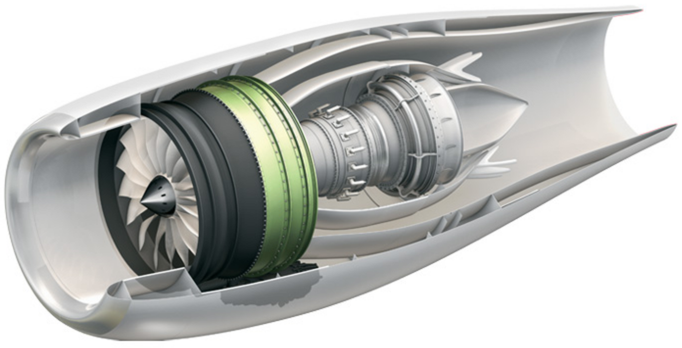
Facilities

Requires high-pressure insert to CIR or a new facility. Ground-based program necessary for engineering/science development.

Impact/Applications – Earth-based

- Supports design of next generation, high efficiency, low emission transportation systems
- Enthusiastically endorsed by industry, academia and government as highest priority, jet engines (GE, UTRC) DoD: (AFOSR), diesel engines (Cummins)





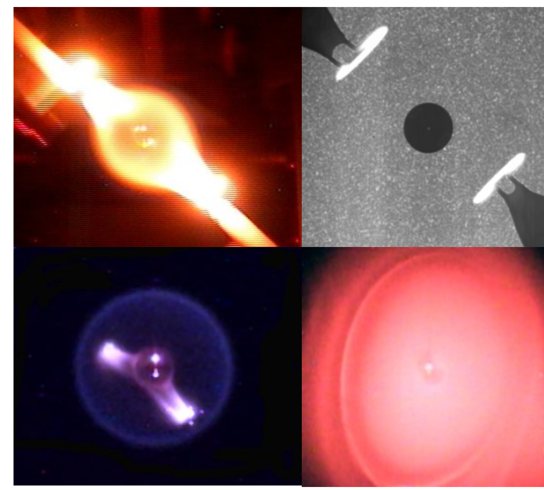
Droplets, Sprays and Aerosols
Cool Flame Combustion of Liquid Fuels
Rank: High Priority #2

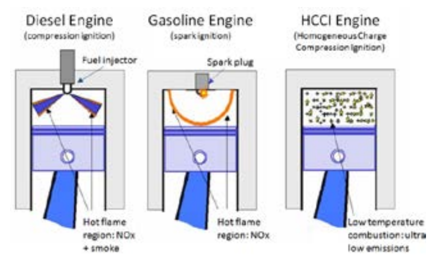
Objective
Obtain benchmark experimental data on the physical and chemical characteristics of pure and fuel-mixture droplets burning in low temperature cool flame regime. Develop detailed and reduced chemical kinetic models validated by experimental data.

Relevance
Fundamental data and models of cool flame and Negative Temperature Coefficient chemistry required to design future high efficiency IC engines, such as Homogeneous Charge Compression Ignition. Droplet combustion data provides unique method to validate and develop chemical kinetic schemes for low and high temperature chemistry. Measured burning rates, flame dynamics (OH* and CH* emissions) and extinction diameters place stringent constraints on physical and chemical kinetic models over a range of residence times.

Facilities
- Utilize existing CIR/MDCA facilities with little to no modifications

Impact/Applications – Earth-based
- High science return with little investment
- Significant interest from industry, academia and DoD





Droplets, Sprays and Aerosols
Biofuel Combustion and Liquid-Phase Circulation and Diffusion Measurements
Rank: High Priority #3

Objective

Obtain benchmark experimental data on the physical and chemical characteristics of biofuels and biofuel surrogates

- Internal circulation and diffusion coefficient measurements during biofuel vaporization and combustion
- Combustion and extinction characteristics of biofuels and biofuel surrogates

Relevance

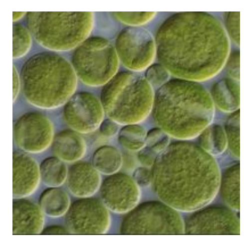
Biofuel chemistry is different from petroleum-based transportation fuels with increased amounts of ethers and esters. Gasification and combustion characteristics of these fuels are poorly understood. Large droplet evaporation and combustion in CIR/MDCA facility should provide time and space resolved data on staged evaporation and cool/hot flame extinction for model development for IC engines and gas turbines.

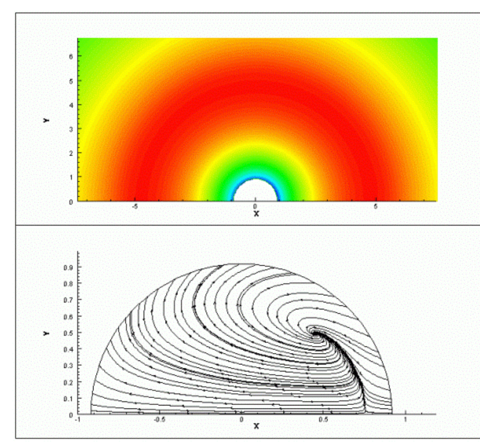
Facilities

- Utilize existing CIR/MDCA facilities with little to no modifications. Builds on prior work with ASI and Cool Flames Investigation.

Impact/Applications – Earth-based

- High science return with little investment
- Significant interest from industry, academia and DoD





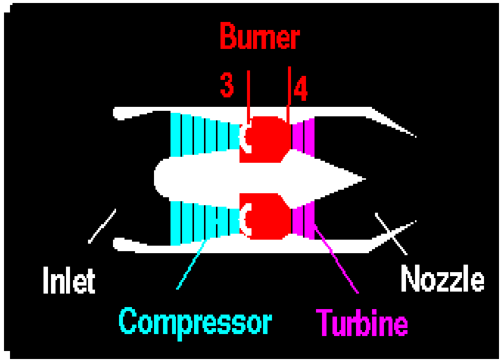
Recommendations

Premixed Flames

1) Laminar Gaseous Premixed Flames
2) Laminar Particle-Air Premixed Flames
3) Nanoparticle Formation in Premixed Flames

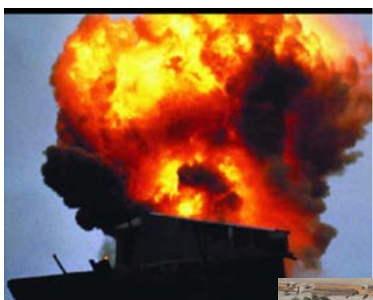
Chair: Elaine Oran/ University of Maryland
Co-chair: Narendra Joshi/ General Electric
Facilitated by: Suleyman Gokoglu, Fumiaki Takahashi, & Uday Hegde

Premixed Flames
Applications



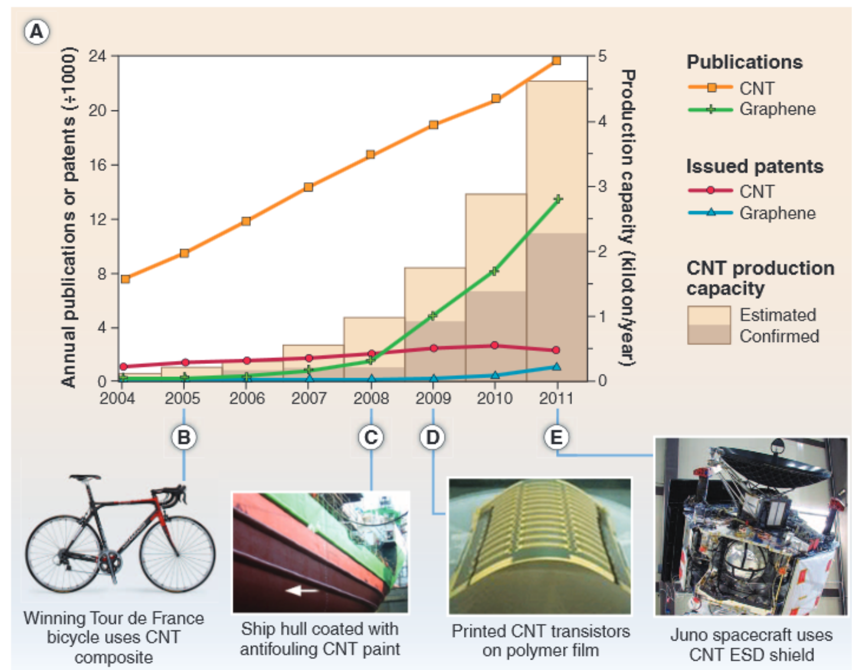
Combustion in stoichiometry gradients powers gas turbine engine

High Lewis number fire from automobile refrigerant leakage (Mercedes-Benz)



More than 450 dust particulate-air explosion incidents recorded between 1980 and 2010. (OSHA Combustible Dust Expert Forum Report, 2011)

Imperial Sugar dust explosion aftermath, Port Wentworth, Georgia, 2008.



Some applications of Flame Generated Carbon Nanotubes, from Volder et al, Science, 2013

Premixed Flames
Properties of Laminar Gaseous Premixed Flames
Rank: High Priority #1

Objective

Map flame propagation and instability in high-Lewis-number* premixed flames and in flames propagating through gradients of stoichiometry. Establish model validation of these conditions.

* *Lewis number = mass diffusivity/thermal diffusivity*

Relevance

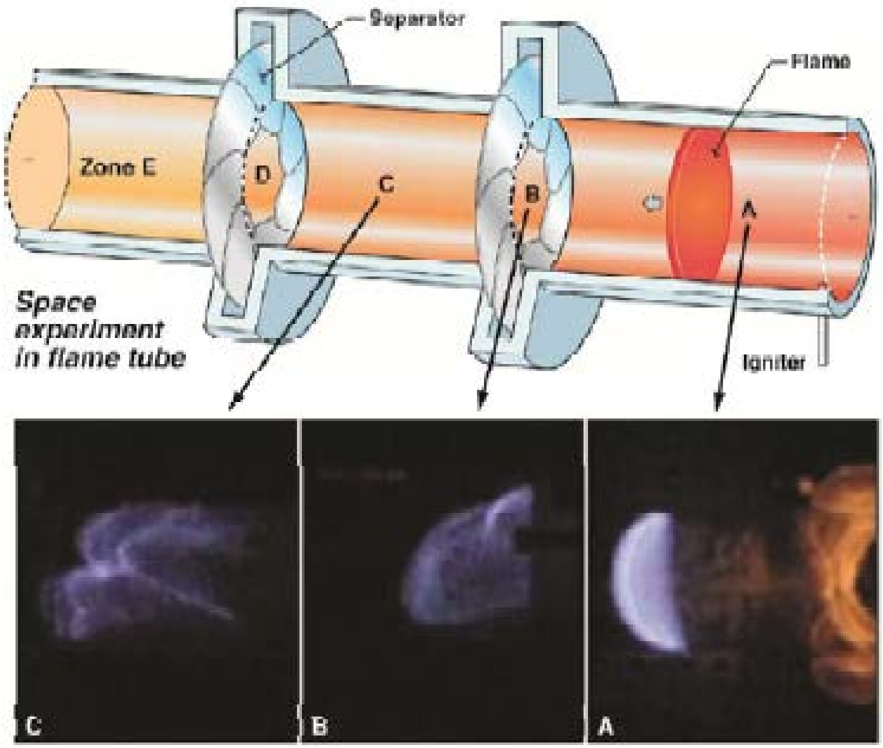
Safety of fuel and refrigerant storage for space missions.
Improvements in the understanding of the turbulence-chemistry interactions critical in the design of aero engines

Impact/Applications – Earth-based

- Promote the safe use of newly mandated refrigerants (which produce high Lewis number flames) in commonplace situations such as household kitchens and automobiles.
- Improved understanding of flame propagation in stoichiometry gradients could lead to better design of combustion systems for power generation and aviation gas turbine engines.

Facilities

- Existing CIR/ACME with a new flame tube/flow tunnel insert for studying premixed flame propagation.



Premixed flame propagation observed in the MIST experiment

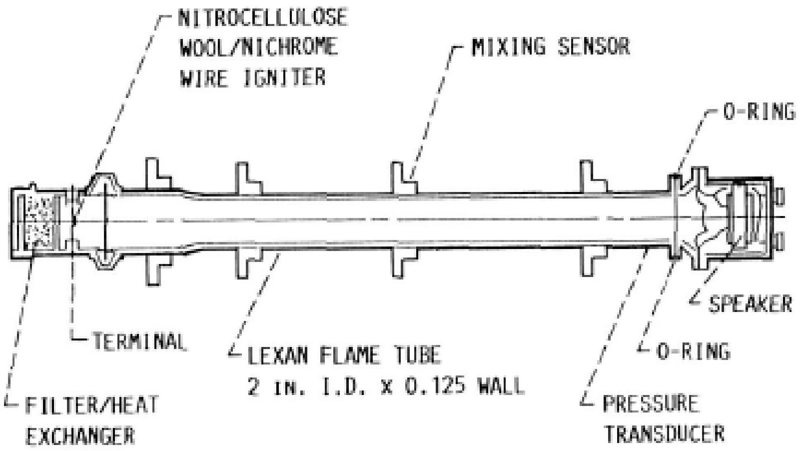
Premixed Flames
Properties of Laminar Particle-Air Premixed Flames
Rank: High Priority #2

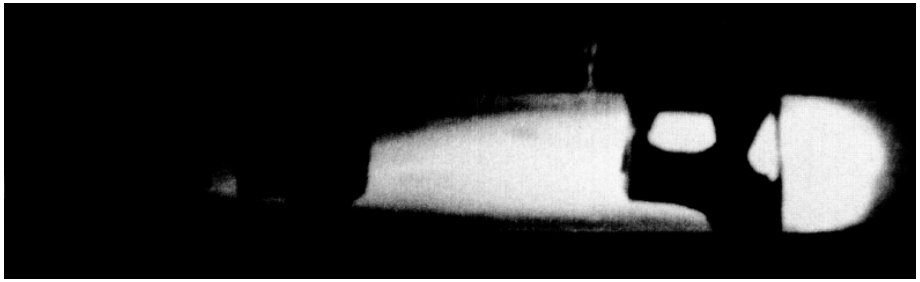
Objective
Measurements of the flame characteristics (speed, structure) and flammability properties of air containing reactive or inert dust characterized by particle sizes of ~10–100 microns.

Relevance
This experiment will improve understanding of an interesting and potentially important area of combustion. The importance extends to issues in safety in dealing with fine-grained materials and possibilities for enhancing combustion in propulsion systems.

Impact/Applications – Earth-based
Improved understanding of the early stages of mixed dust-gas flames that, in later stages, could lead to disastrous explosions. This should produce approaches to mitigation.

Facilities
- Existing CIR/MDCA with a new flame tube insert for studying particle-air premixed flame propagation





Particle cloud flame observed in NASA GRC drop tower

Premixed Flames
Nanoparticle Formation in Premixed Flames with Imposed E-M Fields
Rank: High Priority #3

Objective

Use Electro-Magnetic (EM) fields to align carbon particles formed in a premixed sooting flame in order to form *long-chain* carbon molecules.

Relevance

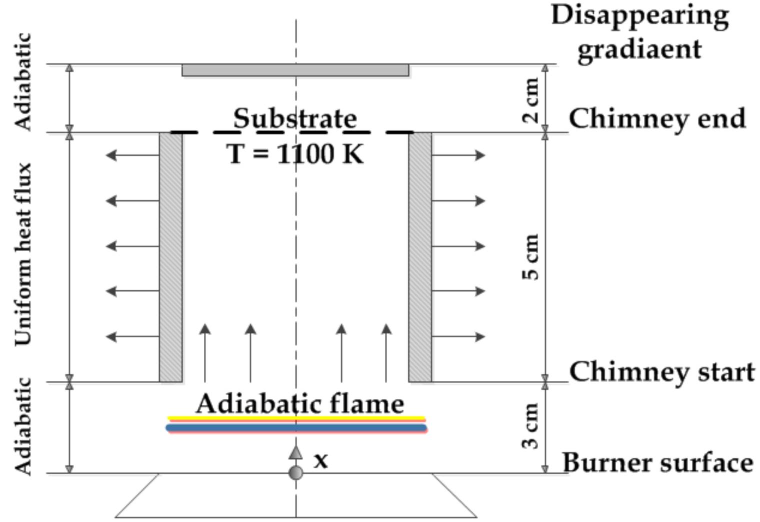
Nanoparticles with unique and desirable properties that could only be formed in space, would enable a space-based manufacturing sector.

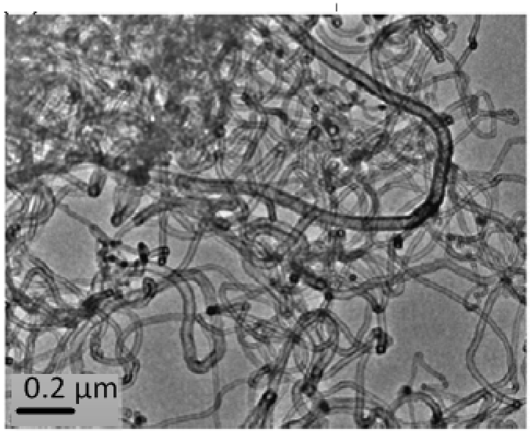
Impact/Applications – Earth-based

If nanoparticles with *unique properties* could be manufactured reliably in space, it could commercialize space.

Facilities

New facilities (new insert for CIR) with enhanced diagnostics will be required





Carbon nanotube production from premixed flat flames (Gopinath & Gore 2007)

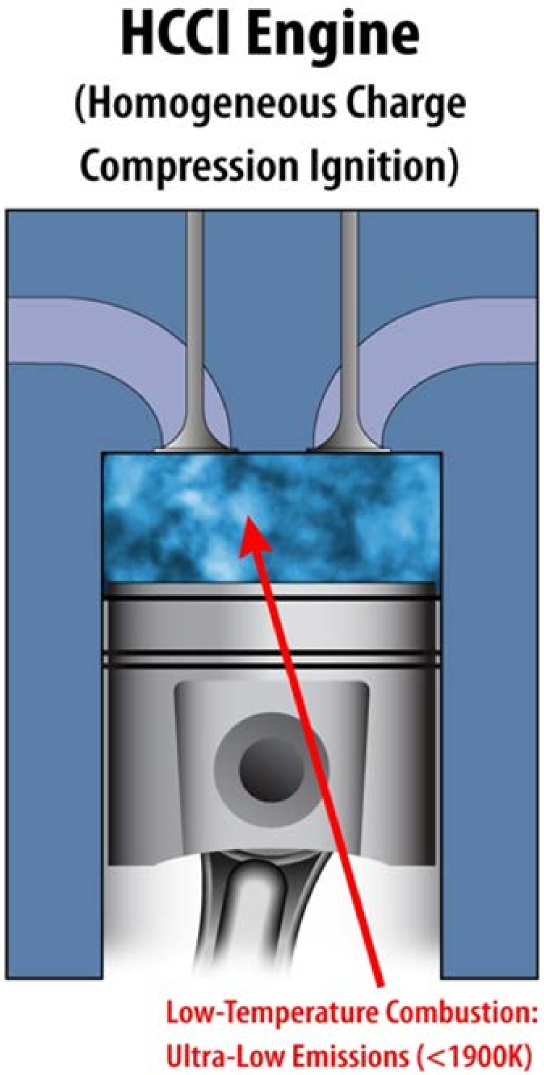
Recommendations

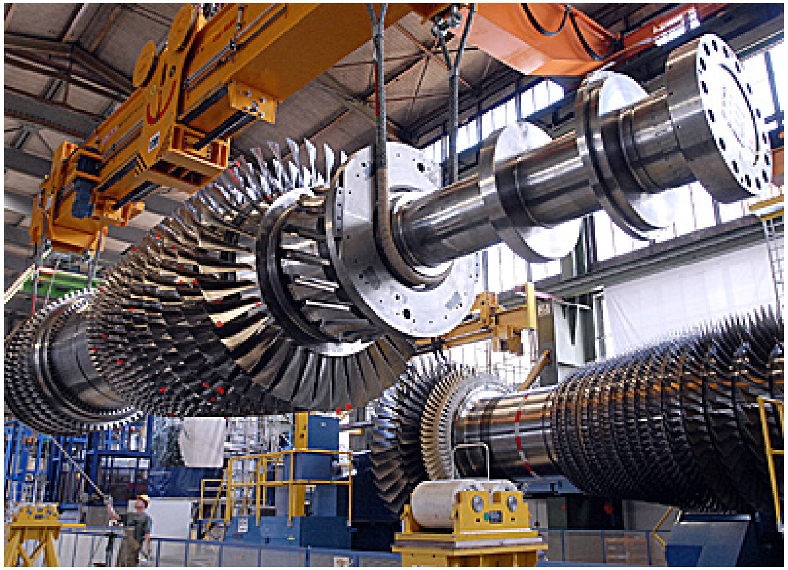
Non-Premixed Flames

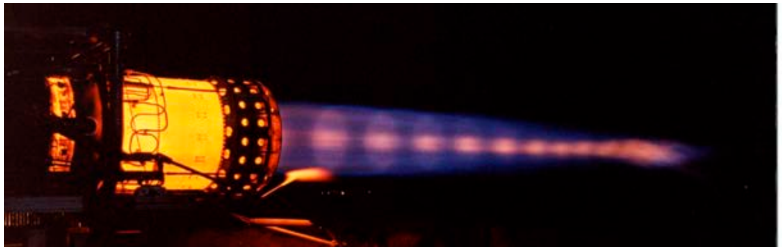
1) Cool Flames
2) Flame Structure at Low Strain Rates

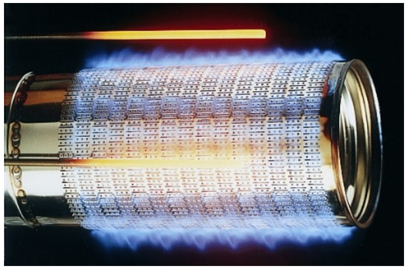
Chair: Kal Seshadri / UC San Diego
Co-chair: Chiping Li / AFOSR
Facilitated by: Dennis Stocker, Fumiaki Takahashi, & Uday Hegde

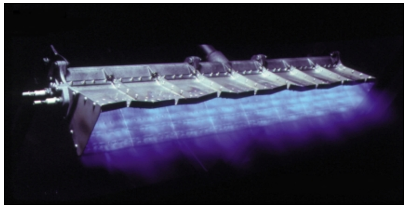
Non-Premixed Flames
Applications




Gas turbine power production


Turbojet with afterburner


Boiler burner


Food processing burner


Furnace burner

Non-Premixed Flames
Cool Flames
Rank: High Priority #1

Objective

- Obtain high-quality experimental data on hot and cool flame dynamics, including for example:
    - conditions at which cool flames occur (e.g., after hot flames) and extinguish,
    - effects of ultra-low convection.

Facilities

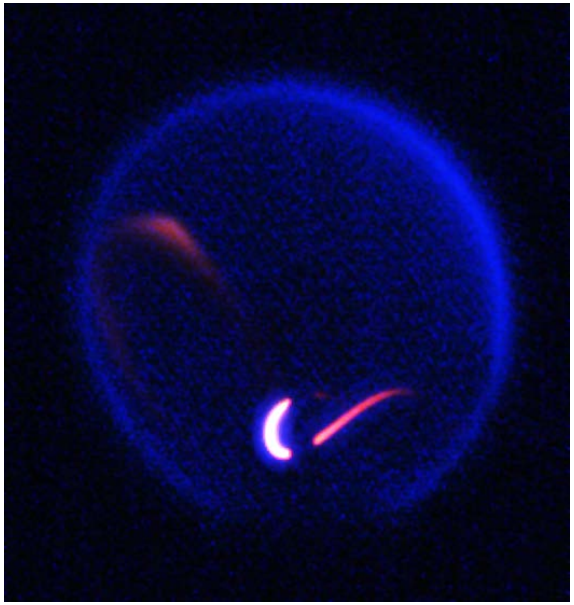
- Use one or more of the following:
    - MDCA (existing hardware) with new components,
    - ACME (now under development) with new parts,
    - Microgravity Wind Tunnel, an envisioned MSG mini-facility replacing that used for BASS, etc.

Relevance

- Novel combustion systems.
- Advanced chemical models enabling the design of:
    - future game-changing HCCI engines,
    - spacecraft propulsion.

Impact/Applications – Earth-based

- Experimental data on cool flame structure and extinction is expected to play a dominant role in prediction of combustion processes in practical systems.



Spherical Non-Premixed Flame
(formed with a porous sintered burner fed with gaseous fuel, where the image was brightened)

Non-Premixed Flames

Flame Structure at Low Strain Rates

Rank: High Priority #2

Objective

- Obtain unique benchmark data to improve fundamental understanding of interactions between transport and chemical kinetics at low strain rates, for example:
    - o data to elucidate the influence of radiative heat transfer and low-temperature chemistry on flame structure and extinction conditions.

Relevance

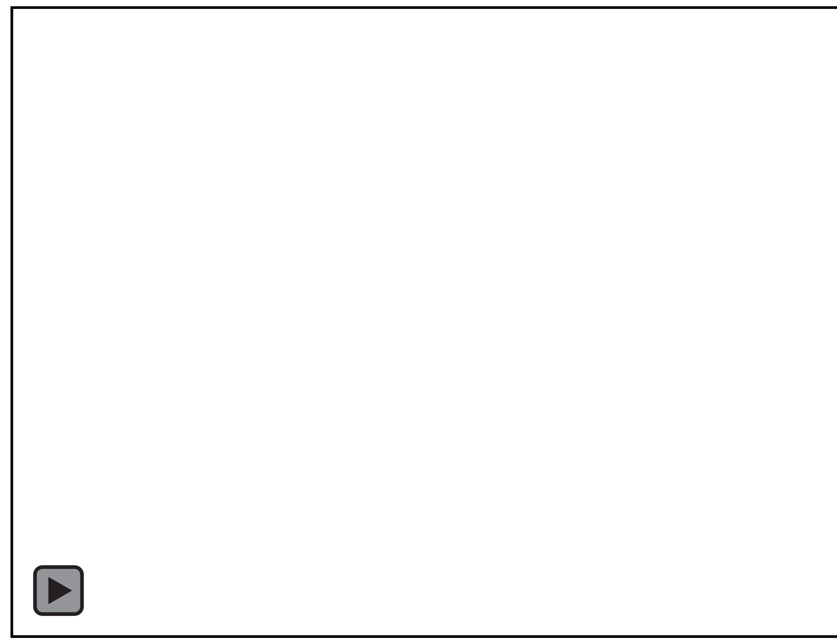
- Improved chemical kinetic data base that could be used in improving predictive capabilities, for example to improve design tools for practical combustion systems.

Impact/Applications – Earth-based

- Improvements to the chemical kinetic data base.
- While the existence of flammability limits for premixed flames are well known, the existence of such limits for non-premixed flames have not been investigated.

Facilities

- Use one or both of the following:
    - o ACME (now under development) with new parts,
    - o Microgravity Wind Tunnel, an envisioned MSG mini-facility replacing that used for BASS, etc.



Soot Escaping a Non-Premixed Flame
(formed with a flat porous burner
fed with gaseous fuel during a 5-s drop test)

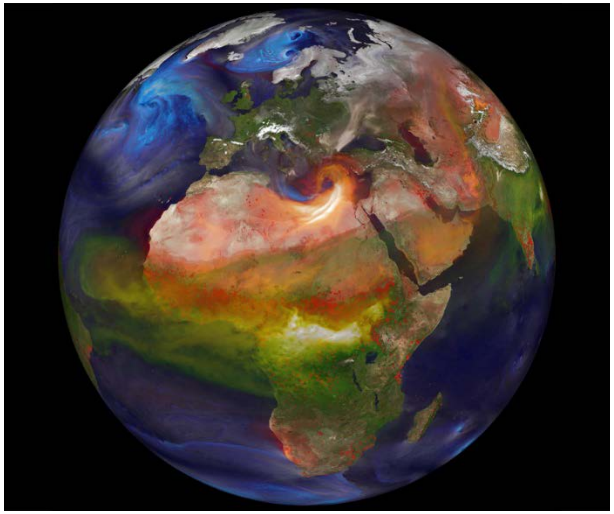
Recommendations

Heterogeneous Reaction Processes

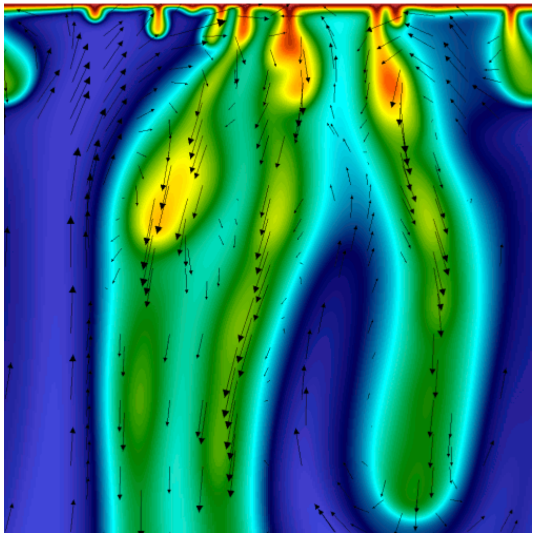
1) Gas/Solid Materials Inter-Conversion
2) Nanoparticle Formation in Flames
3) Carbonaceous Fuel Particle Conversion

Chair: Hai Wang / Stanford University
Co-chair: Christopher Shaddix / Sandia Nat. Lab.
Facilitated by: Suleyman Gokoglu

Heterogeneous Reaction Processes
Applications

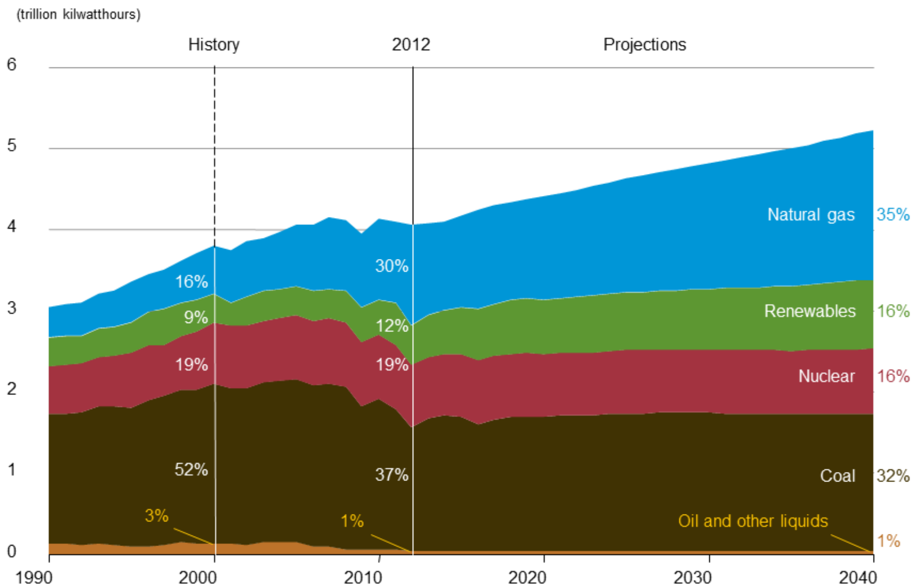


Smoke and soot (green) from biomass burning merge with dust (red) from the Sahara desert (NASA Visualization Explorer 2013)



Buoyancy induced flow vectors during CO_2 sequestration (Lawrence Berkeley Labs)

Prototype ISRU reactor at NASA GRC



Electricity generation by source (United States Energy Information Administration). Coal and natural gas remain primary sources well into the future.

Heterogeneous Reaction Processes
Gas/Solid Materials Inter-Conversion
Rank: High Priority #1

Objective

Quantify the fundamental mechanisms and kinetics of inter-conversion of gas and solid or gas/solid oxidation/reduction reactions for isolated single particles, or arrays of particles.

Relevance

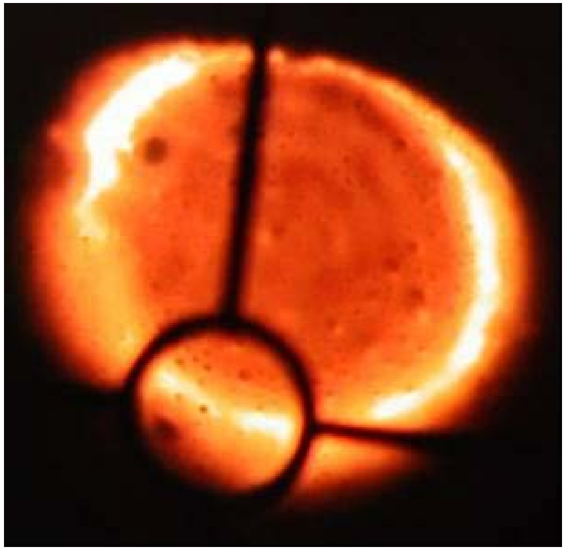
In-situ resource utilization plants are critical to future NASA missions. Testing devices developed for onboard waste management and useful gas production will reduce waste volume onboard of the ISS.

Impact/Applications – Exploration and Earth-based

- In-situ resource utilization in Lunar and Martian environments, space waste management and production of life-sustaining materials (e.g., O_2 & H_2O)
- Terrestrial energy conversion using chemical looping technology to enable economical CO_2 sequestration
- Specialty material synthesis
- Catalysis
- Fire safety

Facilities

- A new insert is needed but could be accommodated in the CIR. A conceptual insert design, incorporating a laser heating source and a carousel with multiple pre-mounted particles on fibers, was discussed during the CombustionLab workshop and found to be potentially feasible with modifications.
- The existing FLEX insert may also be modified to accomplish the objectives of this study.
- Ground-based low-gravity facilities are needed to develop and demonstrate the feasibility of the conceptual insert design.



Molten lunar regolith simulant (JSC-1A) during processing with gas flow (Gustafson et al. 2009)

Heterogeneous Reaction Processes
Nanoparticle Formation in Flames
Rank: High Priority #2

Objective

- Utilize long residence times in low gravity to expand the early soot growth region of flames to quantify growth kinetics.
- Operate flames in conditions to enable production of novel, non-agglomerated nanoparticles.

Relevance

Soot formation is a problem critical to heat management inside rocket engines. A better understanding of soot formation will improve propulsion design and efficiency.

Impact/Applications – Earth-based

- Almost all sectors of combustion-based energy conversion produce soot
- The unique spherical flame design enabled in microgravity can impact the science of soot formation.
- Aerosol dynamics and dispersion is critical to many terrestrial applications, including nanoparticle synthesis and fire safety.
- Design of quantum dot materials is critical to future developments in electronics.

Facilities

- Possible modifications of the existing ACME insert in CIR should enable this study. Enhancements of (mainly optical) diagnostic and measurement capabilities are required to increase scientific return.

A burner stabilized sooty flame in the Zero-Gravity Facility

Heterogeneous Reaction Processes
Carbonaceous Fuel Particle Conversion
Rank: High Priority #3

Objective

Conduct single-particle or particle-array experiments in inert, reducing, and oxidizing environments to uncover fundamental processes in coal and biomass conversion.

Relevance

Conversion of carbon-rich portions of space trash (i.e. trash-to-gas) by providing information useful for the design of devices for in situ resource utilization.

Impact/Applications – Earth-based

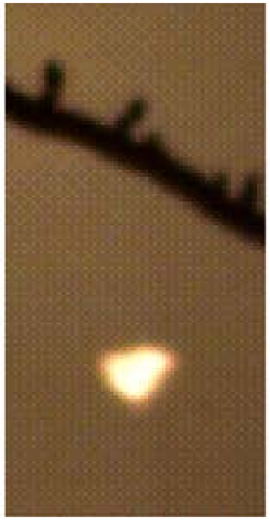
- Over 35% of electrical power is produced from coal combustion, leading to significant emission of air pollutants and greenhouse gases.
- Liquid fuel production from coal and biomass typically use heterogeneous reaction processes that are to be studied here.
- A better understanding of the conversion of carbon-based matter, including coal, biomass, space trash, etc. will enable environmentally benign energy conversion.

Facilities

- A new insert is needed but could be accommodated in the CIR. A conceptual insert design, incorporating a laser heating source and a carousel with multiple pre-mounted particles on fibers, was discussed during the CombustionLab workshop and found to be potentially feasible with modifications.
- The existing FLEX insert may also be modified to accomplish the objectives of this study.
- Ground-based low-gravity facilities are needed to develop and demonstrate the feasibility of the conceptual insert design.

(a)

(b)



Burning of a single coal particle. (a) Volatile flame followed by (b) Char combustion (Maffei et al. 2013)

Recommendations

High Pressure and Supercritical Reacting Systems (HP-ScRS)

1) Droplets and Sprays Transport Properties
2) Hydrothermal Flames
3) Low Temperature Combustion

Chair: William Jacoby / University of Missouri
Co-chair: John Deur / Cummins, Inc.
Facilitated by: Michael C. Hicks & Uday G. Hegde

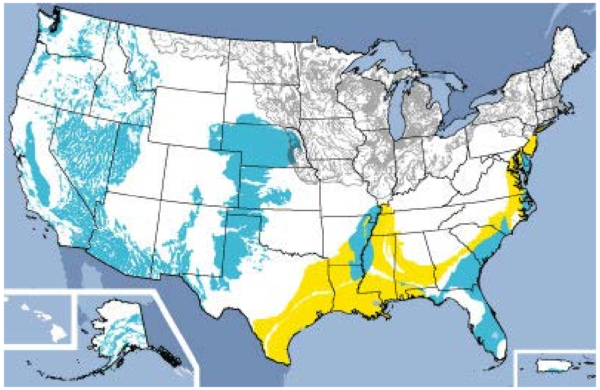
High Pressure and Supercritical Reacting Systems
Applications

- Hydrothermal Flame Research for Supercritical Water Oxidation (SCWO) Applications

waste management

SCWO used for treatment of municipal sludge

water reclamation



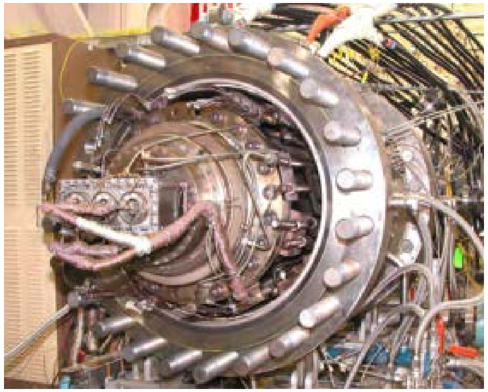
SCWO used for reclamation of brackish water in aquifers

weapon demilitarization

SCWO used for chemical weapon destruction (BlueGrass Army Depot 50 ton/day)

- Droplet and Sprays Transport Properties

high pressure thermophysical properties and combustion chemistry

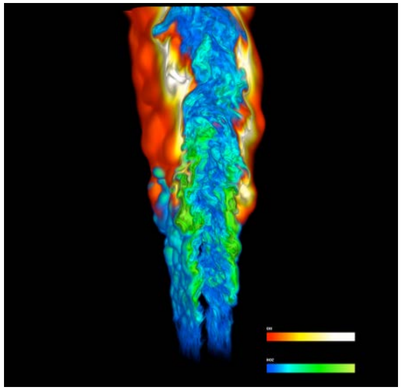


Advanced Subsonic Combustors (test rig at Glenn Research Center)

Diesel engine - high injection pressures

- Low Temperature Combustion -

experimental data needed for numerical validation



(C.S. Yoo, et al., Sandia Labs - 2013)

DNS of high pressure turbulent combustion

High Pressure and Supercritical Reacting Systems
Droplets and Sprays Transport Properties
Rank: High Priority #1

Objective

- Study high pressure droplet formation and combustion at sub- to supercritical conditions
- Study the evolution of liquid/gas interface and identify dominant thermophysical processes and impact on ignition and stabilized combustion during trans-critical burning regime
- Perform high resolution measurements of evaporation rates, species concentrations, and ignition parameters

Relevance

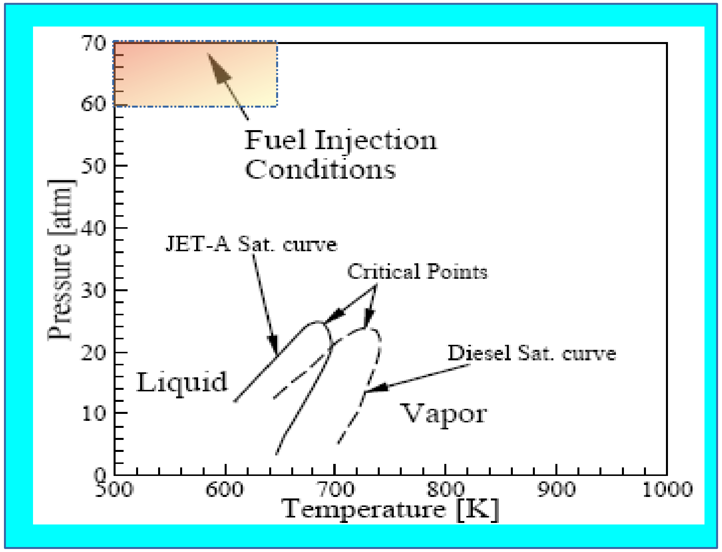
- Practical combustion devices, e.g., internal combustion engines and gas turbines, are trending to supercritical operating pressures
- Chemical kinetics at supercritical pressures are poorly understood (e.g., ignition parameters, reaction rates, intermediate species)

Impact/Applications – Earth-based

- Decrease pollutants from diesel engines (e.g., soot, NOx)
- Enhance diesel engines - allow for operations at higher pressure ratios
- Enhance jet engine design and operations a better understanding of transcritical and supercritical reactant mixing and ignition

Facilities

- New high pressure combustion facility required for ISS based research
- There is a strong interest in a robust ground based program using the ZGF for near-term commercial application



Pressure vs. temperature diagram showing typical high pressure injection conditions with Jet-A and diesel saturation curves

High Pressure and Supercritical Reacting Systems
Hydrothermal Flames
Rank: High Priority #2

Objective

- Determine ignition parameters, flame structure, temperature profiles and reaction mechanisms of ***hydrothermal flames***
- Study supercritical fluid dynamics of injected reactant streams; e.g., flow structure, turbulent transition, reactant mixing, critical transition phenomena

Relevance

- New SCWO reactor designs use ***hydrothermal flames*** for internal heating ... this promises significant reductions in mass and volume, making SCWO feasible for space and extraterrestrial applications

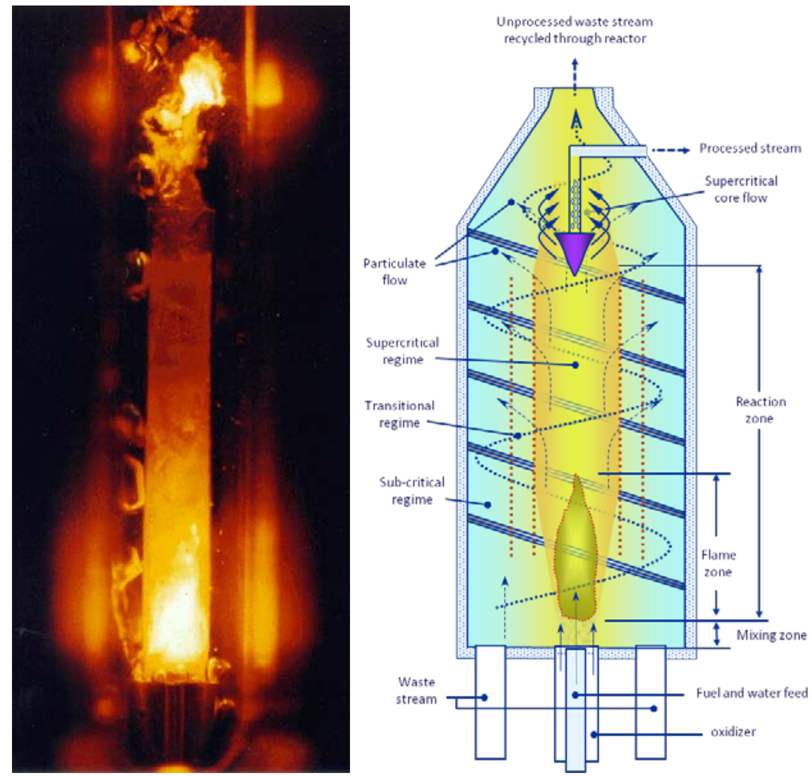
Impact/Applications – Exploration and Earth-based

This research will advance SCWO technology and allow for smaller, lighter and more efficient reactor design and operations benefiting the following SCWO applications:

... space/extraterrestrial resource recovery
... municipal waste streams (e.g., sewage sludge)
... water reclamation (e.g., salt laden aquifers, seawater)
... industrial applications (e.g., agricultural, pharmaceutical)
... resource extraction (e.g., hydrothermal spallation for deep well drilling)

Facilities

- New high pressure combustion facility required
- ZGF to be used for developmental research



Hydrothermal flame (left) *in a supercritical water mixture of methanol at 250 bar using a co-flow burner (Wellig, B. , 2003) and conceptual SCWO reactor **(right)** using flow-stabilized hydrothermal flame for internal heating of reactant flow stream*

High Pressure and Supercritical Reacting Systems

Low Temperature Combustion

Rank: High Priority #3

Objective

- Study and characterize low temperature burning regime (e.g., *cool flames*) and the negative temperature coefficient (NTC) phenomenon associated with hydrocarbon combustion
- Measurements will verify cool flame behavior; flame diameter evolution, flame temperature, and concentration profiles of intermediate species

Relevance

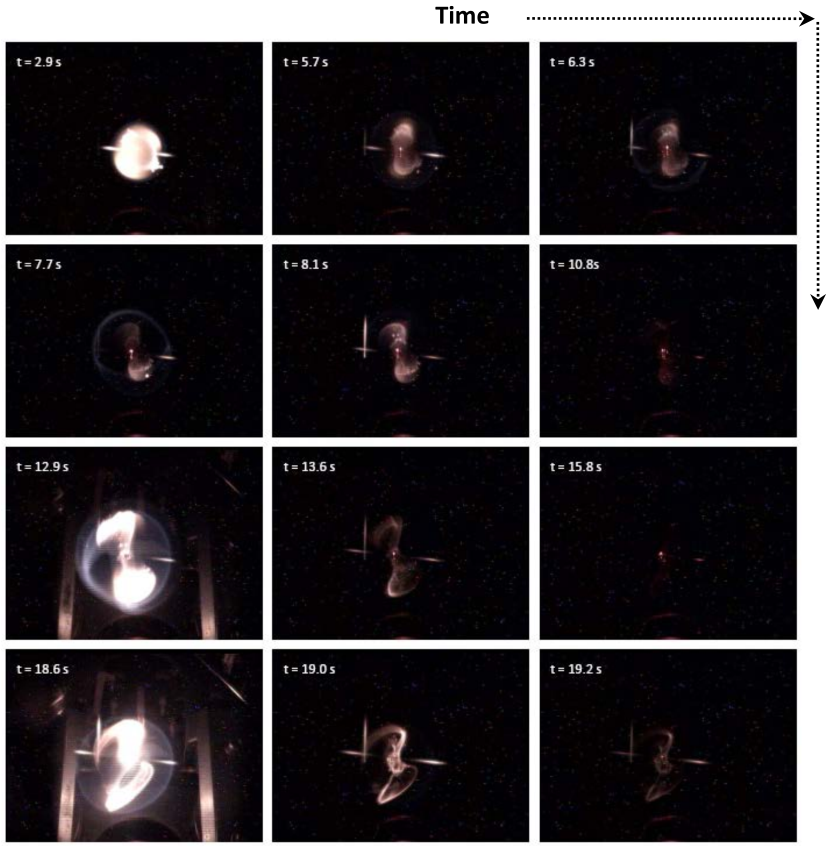
- Current understanding of NTC behavior is based on idealized homogeneous reacting flow experiments, e.g., shock tubes, stirred reactors
- These idealizations do not reflect real combustion devices that often contain large-scale inhomogeneities affecting cool flame behavior - especially true at elevated pressures

Impact/Applications – Earth-based

- Enhance diesel engine design by allowing operations at reduced temperatures
- Reduction in NOx with lower combustion temperatures

Facilities

- New high pressure combustion facility required
- ZGF to be used for developmental research



Time lapse image from ISS FLEX testing of re-ignited aerosol following an extensive period of low temperature burning w/ no visible flame

Overall Recommendation and NRA plan

Open Science NRA - Approach

- The Open Science NRA will target high-priority recommendations from the CombustionLab and FluidsLab Reports.
- Science Definition Teams (SDTs) will be selected through an NRA or appointed. Each SDT will conduct experiments for the broader research community.
- The general approach to develop the CombustionLab and FluidsLab programs is to 1) start with an NRA soliciting proposals using existing hardware followed by 2) a future NRA soliciting proposals to use larger, new hardware builds to enhance capability. Ideally, the NRA solicitations would not be limited to any particular field in combustion science or fluid physics.
- Collaboration with Other Gov't agencies, CASIS, Industry, International Partners, including Roscosmos, will be encouraged.
- The CombustionLab and FluidsLab data will be accessible through the Physical Science Informatics System.

CombustionLab/FluidsLab NRA: near term plan representative solicitation scenario*

Current Hardware (samples/modest hardware mods)

COMBUSTION

- SoFIE insert: Spacecraft Fire Safety - materials flammability

- MDCA insert:
  - Droplets Sprays and Aerosols - cool flames; biofuels.
  - Non-Premixed - cool flames

- ACME insert:
  - Premixed Flames - new flame tube/flow tunnel inserts for studying flame propagation; particle-air flame propagation.
  - Non-Premixed - cool flames; flame structure at low strain rates.
  - Heterogeneous Reaction Processes – Nanoparticle Formation in Flames

* A typical SDT consists of 3 investigators per subtopic

Future CombustionLab NRA: new hardware builds to enhance capability

- **Combustion - New Larger Hardware Builds and Capability** (Facilities, Inserts, etc.)
  - Microgravity Wind Tunnel: 1) Spacecraft Fire Safety - materials flammability. 2) Non-Premixed - cool flames and flame structure at low strain rates - MSG
  - High Pressure Combustion Facility: 1) Droplets, Sprays and Aerosols 2) High Pressure and Supercritical Reacting Systems – 1) Droplets and Sprays Transport Properties, 2) Hydrothermal Flames, and 3) Low Temperature Combustion
  - Resupply vehicle return: Spacecraft Fire Safety - large scale fire for materials flammability (collaboration with AES)
  - Nanoparticle Formation with Imposed E-M Fields Insert: Premixed Flames
  - Solid Particle Reaction Insert: Heterogeneous reaction processes 1) Gas/Solid Materials Inter-Conversion and 2) Carbonaceous Fuel Particle Conversion: